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FAILURE ANALYSIS OF FRACTURED CAPSCREWS IN CENTRIFUGAL COOLANT COMPRESSOR

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FAILURE ANALYSIS OF FRACTURED CAPSCREWS IN CENTRIFUGAL COOLANT COMPRESSOR

This study was requested by Plant Engineering to determine the cause of failure of capscrews that retain a baffle plate in a Freon 11 centrifugal compressor manufactured by the Trane Company. The affected unit is installed in Building 490 at LLNL.

CONCLUSIONS

1. The capscrews failed through hydrogen embrittlement. The source for hydrogen appears to have been corrosion.

2. In a dissimilar metal couple of aluminum and uncoated high strength, highly-stressed steel, corrosive environments would generate hydrogen at the steel side of the couple and embrittle it.

3. There is no evidence that the manufacturer took precautions to prevent such an occurrence. Since other LLNL units of the same construction may be similarly affected, it is recommended that details of the failures and results of this study be brought to the attention of the compressor manufacturer for resolution and recommendation of proper alloy and/or redesign to prevent subsequent failures.

BACKGROUND, AS UNDERSTOOD

After some 1,000 hours of operation since originally installed in Building 490, the coolant compressor experienced a bearing failure. Its repair required disassembly of the compressor, including removal of the aluminum baffle plate. This is a stationary member attached to the cast iron compressor housing by eight (8) steel socket-head capscrews (3/8 inch diameter, 16 threads/inch, 3 inches long, 1 1/2 inch threaded portion).

Upon disassembly of the compressor, two capscrews broke during attempts to remove them. According to the mechanic who removed the screws, they broke just under the socket-head with minimal force.

After replacement of the failed bearing, the aluminum baffle plate was re-installed. Two new capscrews from LLNL stock were used to replace the two broken ones. The LLNL screws were visually identical in all respects to the original screws, except for a somewhat different spacing of the knurl pattern around the periphery of the cap and for a slight difference in the socket configuration. (These distinguishing characteristics become important in identifying components that fail later.)

The screws were re-installed according to recommendations of the compressor manufacturer (Trane). That is, the screw threads were coated with an application of "Lock-Tite" compound (in lieu of lockwashers) and tightened with a torque wrench to 24 foot-pounds.

The reassembled compressor was returned to service and ran for about a week before a metallic noise was heard coming from the compressor. It was shut down, disassembled, and the fractured head (or cap) from one of the original lot of capscrews retaining the aluminum baffle plate was found loose inside the compressor chamber. The aluminum impeller and baffle plate had been chipped and damaged by the broken capscrew head.

Once again, the baffle plate assembly was removed to evaluate the extent of the damage caused by the capscrew that had broken off. Upon disassembly, two more capscrew heads broke off with minimal force when they were attempted to be removed. From characteristics noted previously, these two failed capscrews also were identified as being of the original lot of eight screws, and not the LLNL replacements.

At this point, Plant Engineering contacted the Physical Metallurgy Section for an assessment of the cause of the capscrew failures and for a recommendation to prevent recurring failures. They supplied, for examination, three broken capscrew heads (including the one that failed while the compressor was running), one shank remaining after the head had fractured, one of the three remaining intact original capscrews, and several of the replacement LLNL capscrews.

EXAMINATION PROCEDURE

The fractured screw heads were ultrasonically cleaned of oil and grease using acetone and ethyl alcohol, then dried in compressed air. The fractured surfaces were examined as-is, without sectioning or other preparation, in both an optical stereo-microscope and a scanning electron microscope (SEM) at various magnifications up to 10,000x to characterize the fracture and other features.

One intact sample of each kind of capscrew (original and LLNL replacement) was cross-sectioned about 3/8 inch from the underside of the cap, then cut longitudinally down the axis, to provide a cross-section of the cap and cap-to-shank transition region which was the site of all the capscrew failures. These two longitudinal sections (one from each type of capscrew) and a shank cross-section of each were mounted in Lucite, polished and etched for metallographic examination.

Microhardness measurements were made of these polished surfaces and standard Rockwell hardness determinations, to the extent possible, were made on the remaining (unmounted) halves from each longitudinal section. Hardness measurements also were made on the external surfaces of the unthreaded portion of the screw shanks.

RESULTS OF EXAMINATIONS

At low magnifications (up to about 60x) in the optical microscope, the screw heads and fracture surfaces showed no evidence of deformation, as would be expected if the fractures had been caused by simple overload in tension or torsion. The fractures were fairly flat and brittle-appearing. A whitish residue that persisted through the ultrasonic cleaning operations was evident on the fracture surfaces, generally confined to one fracture edge in an area of about 150 degrees of its periphery.

In the SEM, the fracture surfaces were found to be comprised of two basic fracture modes: (a) brittle, intergranular cracking around the periphery of the fractured surface, and (b) predominantly ductile-dimple type fracture nearer the center. Mixtures of the two fracture modes were found in regions in-between. Figure 1 shows the appearance of the brittle-fracture region.

The white residue on the fracture surfaces was chemically analyzed in the SEM using energy-dispersive x-ray spectroscopy techniques with the following results:

Element	Weight %
Aluminum	73.97
Silicon	10.28
Chlorine	5.97
Iron	9.78

Metallographic specimens from unfailed capscrews of both sources (originally supplied with the compressor and the LLNL replacements for the fractured originals) were first examined in the as-polished, unetched condition. This showed the original capscrew to have some agglomerated non-metallic inclusions oriented in the axial direction. At similar magnifications, the LLNL-supplied capscrew had a lower inclusion population.

Etching revealed a fine-grained microstructure of tempered martensite and bainite in both, but the microstructure of the LLNL-supplied capscrew had finer microstructure. At higher magnifications, both exhibited scattered discontinuous non-metallic stringers oriented axially. Neither specimen exhibited evidence of intergranular attack, cracking, other metallurgical defects or unusual features.

DISCUSSION OF RESULTS

The screw fractures apparently initiated around the periphery of the capscrew shank (at the crevice formed by the shank and protrusion of the head) through the embrittled regions, causing a reduction in the load-carrying area of the capscrew shank. This would have increased the unit tensile stress in the screw, making it fracture through tensile overload (at the central core of the screw shank) when the applied unit stress exceeded its tensile strength.

In four out of the five capscrew failures, the final fracture occurred during attempts to remove the screws. However, in the one case, the increase in tensile stress, probably through unequal expansion of the steel screw/aluminum baffle plate combination as it became heated during compressor operation, furnished an additional tensile load apparently sufficient to fracture the screw head.

The evidence gathered in this brief study points to hydrogen embrittlement as the cause of the capscrew failures (1)(2). However, hydrogen embrittlement requires, among other conditions (all of which appear to be present), a source of hydrogen. In the absence of other indications, it might be concluded that the screws somehow became embrittled before they were installed in the compressor. But there is evidence that the embrittlement probably occurred while they were installed in the compressor.

Under ordinary circumstances, and without other indications to the contrary, such an application as this would not generate hydrogen in the region of the capscrew head. That is, unless there were an electrochemical reaction there. And there _is_ evidence of such a reaction in that location.

From EDS analysis, the white residue appears to be an aluminum salt, probably a product of a corrosion process occurring at the juncture of the unprotected steel capscrew and the aluminum baffle plate it secures. This dissimilar metal couple could generate hydrogen at the surface of the steel screw, as the adjacent aluminum corrodes (3)-(5).

Since the compressor chamber is filled with Freon 11 and operates dry and at a slightly elevated temperature (estimated at 150 F), operating conditions do not appear conducive to corrosion. However, it is possible that exposure to moist marine atmospheres during shipment or at some other time could have furnished conditions capable of causing corrosive attack at the capscrew head, with accompanying generation of embrittling hydrogen.

This location is especially vulnerable to hydrogen embrittlement as it is the site of highest tensile stress concentration. Conservative calculations of average tensile stress in the capscrew shank reveal a static stress level greater than 100 ksi simply due to torquing the screws to 24 foot-pounds. Concentrated stresses at the junction of the head and the shank - the site of the fractures - could be much higher.

From hardness readings of 40-44 Rc (converted from Knoop scale), the capscrews are estimated to have a tensile strength of around 200 ksi (6). Tensile stress conditions at the site of fracture are considered sufficient to develop hydrogen embrittlement in steels of such strength levels.

Without information on atmospheric conditions the compressor was subjected to before or during its delivery to LLNL, it is pointless to speculate on what conditions existed or how they may have contributed to embrittlement of the capscrews that led to their failure. Nevertheless, the evidence is strong that at sometime before it was placed in service the compressor (its internal cavity presumably open to ambient atmosphere before installation) was exposed to conditions that supplied moisture - possibly chloride-laden moisture - to the region of the baffle plate.

It is apparent that no precaution during manufacture of the compressor was taken against such potentially damaging conditions; as bare, uncoated steel capscrews under high tensile stress were placed in direct contact with aluminum. It is well known that, under conditions of moisture and possibly dissoved salts, this dissimilar combination can cause corrosion of the aluminum (becoming the anode), with accompanying evolution of hydrogen at the cathode (the steel screw, in this case). The phenomenon of embrittlement of highly-stressed high strength steel by hydrogen under such conditions is similarly well known (7).

Until the source of suspected corrosion has been identified, and there is assurance that it will not recur during the lifetime of the compressor, it would be imprudent to re-install capscrews of the same type as originally used. Some consideration, therefore, should be given to preventing capscrew embrittlement.

Prevention can take various directions. Probably the most direct route is through a significant reduction in the level of tensile stress in the capscrews. This might be done by torquing to lower levels or using larger diameter screws (requiring redrilling and retapping all members).

Coating the screws (through cadmium plating, for example) is often considered a possible solution to corrosion-related deterioration of steel fasteners. However, the cadmium plating operation charges the steel with hydrogen and could cause the same kind of failure as has already been experienced (8). Therefore, it is important that any plated screws are baked for a sufficient length of time and at high enough temperature to remove the hydrogen introduced during the plating operation. Unfortunately, this is not always a reliable means of removing all hydrogen from cadmium-plated steels (9). Accordingly, before cadmium-plated or other coatings are considered a solution, confirming (mechanical) tests should be run on plated + baked screws to assure that the hydrogen has been removed.

Another possible means of control would be to use screws of an alloy that is less susceptible to hydrogen damage. Alloys containing nickel usually are less prone. Whatever alloy is chosen, it must have sufficient tensile strength to sustain the required load. The P-H (precipitation-hardened) stainless steels are a possibility; however, these alloys are not immune to hydrogen embrittlement and a proper grade and heat treatment must be used to afford the best balance of properties for the application.

When seeking capscrews of materials that could offer some resistance to hydrogen embrittlement, the expedient of machining capscrews from solid stock may be a means offered by suppliers for obtaining screws of the desired material. But this may not be a good approach as it does not provide the favorable grain flow configuration in the critical head-to-shank region that die-forge-upset headed screws have. That is, they may fail prematurely under high stresses.

To summarize the situation briefly, there is no panacea for curing hydrogen embrittlement at the junction of a dissimilar metal combination operating under high stress and in the presence of atmospheres conducive to corrosion. For this reason, among others (including issues involving liability of the compressor manufacturer), details of the occurrences of failure of these capscrews and results of this study should be brought to the attention of the compressor manufacturer for resolution and recommendation of the proper hardware and installation procedure for avoiding recurrent failures in this and similar compressors at LLNL.

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CEWitherell
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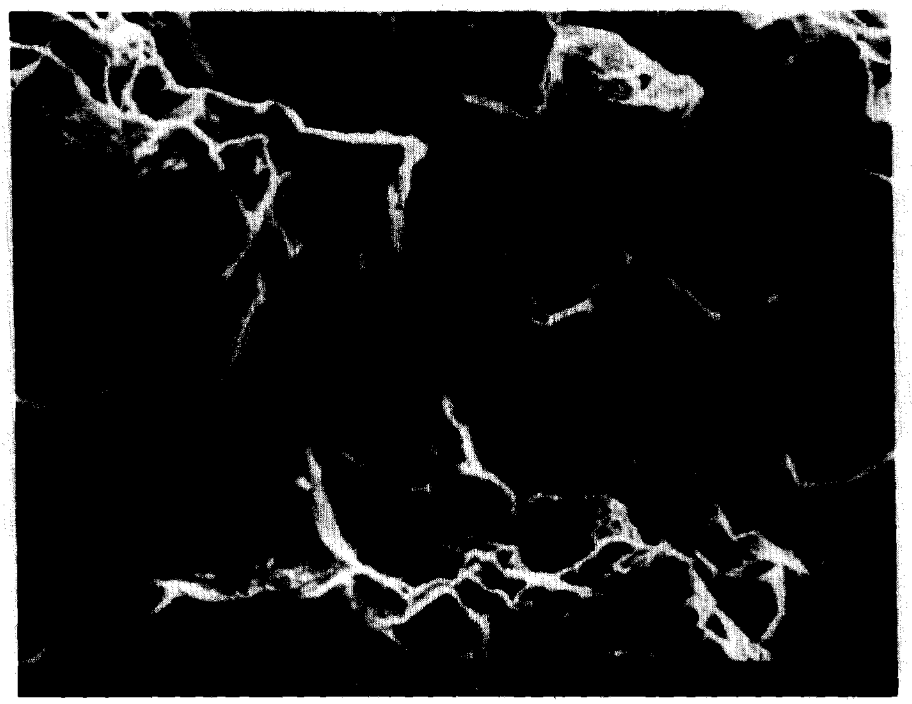
Magnification: 1,300X



Magnification: 1,400X

FIGURE 1

Appearance of Peripheral Regions of Fracture Surface
of Centrifugal Compressor Capscrews